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With AFOSR support, a new strategy called"cyclic switching" has been devised for dealing with the well-known, long standing, certainty equivalence control synthesis problem which arises in the design of identifier-based adaptive controllers because of the existence of points in the parameter space where the design model upon which certainty equivalence synthesis is based, loses stabilizability. The concept is, provably correct, easily implemented, and applicable to both siso and mimo linear systems, whether they are minimum phase or not.

The feasibility has been established of an entirely new method of supervisory control called "dwell-time switching". Dwell time switching is a simple on-line logic capable of determining in real time which controller from a family should be put in feedback with a process as to achieve satisfactory performance. The method is intended to be used in situations where there is substantial process model uncertainty, so much in fact that no single fixed parameter, linear control can possibly work.

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FINAL TECHNICAL REPORT
on the project
ADAPTIVE STABILIZATION OF LINEAR AND NONLINEAR SYSTEMS

for the period
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Abstract

With AFOSR support, a new strategy called "cyclic switching" has been devised for dealing with the well-known, long-standing, certainty equivalence control synthesis problem which arises in the design of identifier-based adaptive controllers because of the existence of points in the parameter space where the design model upon which certainty equivalence synthesis is based, loses stabilizability. The concept is provably correct, easily implemented, and applicable to both siso and mimo linear systems, whether they are minimum phase or not.

The feasibility has been established of an entirely new method of supervisory control called "dwell-time switching". Dwell-time switching is a simple on-line logic capable of determining in real time which controller from a family should be put in feedback with a process so as to achieve satisfactory performance. The method is intended to be used in situations where there is substantial process model uncertainty, so much so in fact that no single fixed-parameter, linear control can possibly work.

Introduction

This is the final technical report on research carried out with the support of AFOSR under Grant F49620-92-J-0077. The report consists of the following sections:

A. Research Objectives

B. Research Status

C. Publications

D. Participating Professionals

E. Presentations

F. Discoveries

G. Award

A. Research Objectives

The central goal of this research project has been to develop practical analysis and synthesis methods for dealing with the engineering problems encountered in the design of controllers for aerospace systems admitting models with large uncertainties. In attaining this goal we have sought to resolve three major issue:

1. Develop a practical technique for dealing with the well-known certainty equivalence control synthesis problem which arises in the design of identifier-based adaptive controllers because of the existence of points in the parameter space where the design model upon which certainty equivalence synthesis is based, loses stabilizability.
2. Develop the tools and concepts needed to simplify recently devised adaptive control algorithms intended for the regulation of nonlinear systems.
3. Develop an easily implemented method of supervisory control, which is inherently robust, which is compatible with contemporary linear feedback theory and which can be applied in situations where there is process model uncertainty significantly greater than that which can be dealt with using a single, fixed parameter, linear controller.

B. Research Status

With AFOSR support we have prepared and/or published during the past two calendar years, nine full length journal papers [1-3,5,7-11], three conference papers [4,13,14], one doctoral dissertation [12], and one technical note [6]. Two additional full length papers will be published this spring [15,16], and a preliminary version of [19] has been accepted for publication as a full length paper. Of these, papers [4-6,10-12,15,16] are all motivated by research objective 1 above. Papers [2,3,7,8] are concerned with the development adaptive controls for nonlinear systems, and thus relate to research objective 2. Papers [13,14, 17-20] are prompted by research objective 3.

The idea of cyclic switching introduced in [15], provides a remarkably simple and effective answer to one of parameter adaptive control's knottiest questions: How should an identifier-based adaptive controller be defined at those points in parameter space where certainty equivalence control is impossible? Cyclic switching is unquestionably the most promising way we know of for dealing with this problem.

In [16], the findings of [15] are extended to mimo systems. While [16] proves feasibility of cyclic switching for mimo systems, the important practical issue of how to synthesize a cyclicly-switched controller in an efficient manner is left unresolved, and is therefore under study.

A possible shortcoming of cyclic switching, and for that matter all methods based on indirect control parameterizations, is the possibility of misbehavior resulting from nominal model overmodeling. The "overmodeling problem" is discussed in the concluding remarks of [15]. Algorithms not susceptible to this problem are typically of the direct control type. Until recently such algorithms have been limited to use only with minimum phase nominal process models. In [11] this limitation is overcome by exploiting a new direct control parameterization, and a new method of discrete-time parameter tuning together with the concept of "hysteresis switching" discussed in [5]. What results is a direct control algorithm, not depending on process excitation, which is applicable to the *entire* class of discrete time, siso, nominal process models of McMillan degree not exceeding a prescribed integer n. We know of no other algorithm with this capability. We are continuing to study this approach with the aim of developing similar methods for continuous time systems.

Most of our effort within the past year has been focused on the development and analysis of intelligent switching logics for the supervisory control of families of linear systems. We have

developed a simply-structured, 'high-level' controller called a 'supervisor' which is capable of switching into feedback with a siso process, a sequence of linear positioning or set-point controllers from a family of candidate controllers so as to cause the output of the process to approach and track a constant reference input. What makes the proposed supervisor distinctly different from other algorithms which might be used for the same purpose is the philosophy underlying the method it uses to carry out its task. In particular, the supervisor decides which controller to put in feedback with the process, not by going through an an exhaustive search - i.e., by experimentally evaluating each and every candidate controller's performance by briefly applying it to the process - but rather by continuously comparing in real time suitably defined normed values of 'output estimation errors' generated by the candidate controllers, whether or not they are in feedback with the process. Motivation for this idea is obvious: the controller which generates the 'smallest' output estimation error ought to have the best idea of what the process is and thus should be able to do the best job of controlling the process. The origin of this idea is of course the concept of certainty equivalence from parameter adaptive control.

The subject of supervisory control is treated in papers [13], [14], [17-20]. Reference [19] gives a complete description of what is meant by a "supervisor" and by a "dwell time switching logic." The paper develops a number of tools for analyzing a supervisory control system and uses them to predict closed-loop behavior under certain assumptions. Reference [20], which is in preparation, will give theoretical and experimental proof that the supervisor developed in [19] - without any modification - can in fact perform its function in the face of modeling errors of the unstructured type. Moreover it will be shown that such a supervisory control system cannot be destabilized by bounded disturbances. While these results are only theoretical, they certainly do put supervisory control in a class by itself. To the best of our knowledge, there does not exist an adaptive control method with comparable properties. We have embarked on an extensive simulation study and hope to demonstrate conclusively that many of the shortcomings of adaptive algorithms are not shared by supervisory control.

C. Publications

[1] A. S. Morse, "Towards a Unified Theory of Parameter Adaptive Control - Part II: Certainty Equivalence and Implicit Tuning," *IEEE Trans. Auto. Control*, January, 1992, pp. 15-29.

[2] A. S. Morse, " A Comparative Study of Normalized and Unnormalized Tuning Errors

in Parameter-Adaptive Control," *International Journal of Adaptive Control and Signal Processing*, July, 1992, pp. 309-318.

[3] I. Kanellakopoulos, P. V. Kokotovic, and A. S. Morse, "Adaptive Nonlinear Control with Incomplete State Information," *International Journal of Adaptive Control and Signal Processing*, July 1992, pp. 367-394.

[4] A. S. Morse, "Adaptive Control of One-Parameter Families of SISO Linear Systems," *Proc. 1992 IFAC Symp. on Adaptive systems in Control and Signal Processing*, Grenoble, July, 1992.

[5] A. S. Morse, D. Q. Mayne and G. C. Goodwin, "Applications of Hysteresis Switching in Parameter Adaptive Control", *IEEE Trans. Auto. Control*, v. 37, September, 1992, pp. 1343-1354.

[6] F. M. Pait and A. S. Morse, "Global Tunability of One Dimensional SISO Systems,' *IEEE Trans. Auto. Control*, October, 1992, pp 1605-1608.

[7] I. Kanellakopoulos, P. V. Kokotovic and A. S. Morse "Adaptive Output-Feedback Control of a Class of Nonlinear Systems," *IEEE Trans. Auto Control*, November, 1992, pp. 1666-1682.

[8] A. S. Morse, "High-Order Parameter Tuners for the Adaptive Control of Nonlinear Systems," *Robust Control*, Tokyo , Springer Lecture Notes on control and Info Sci,v. 183, Fall, 1992, 138-146

[9] I. Kanellakopoulos, P. V. Kokotovic and A. S. Morse, "A Tookit for Nonlinear Feedback Design," *System and Control Letters*, 1992, pp. 83-92.

[10] "High-Order Parameter Tuners for the Adaptive Control of Linear and Nonlinear Systems," Proc. U.S.-Italy Joint Seminar on *Systems, Models and Feedback: Theory and Applications*, Birkhauser, Capri, June, 1992, pp. 339-364.

[11] A. S. Morse, "A Gain Matrix Decomposition and Some of Its Applications," *System and Control Letters*, v. 21, 1993, pp. 1-10.

[12] F. M. Pait, *Achieving Tunability in Parameter-Adaptive Control*, Yale university Doctoral Dissertation, 1993.

[13] A. S. Morse, " Dwell-Time Switching," *Proceedings of the Second European Control Conference*, 1993, pp. 176-181

[14] A. S. Morse, "Supervisory Control of Families of Linear Setpoint Controllers," *Proc. 1993 IEEE CDC*, pp. 1055-1060.

[15] F. M. Pait and A. S. Morse, "A Cyclic Switching Strategy for Parameter-Adaptive Control," *IEEE Trans. Auto. Control*, to appear.

[16] A. S. Morse and F. M. Pait, "MIMO Design Models and Internal Regulators for Cyclicly-Switched Parameter-Adaptive Control Systems," *IEEE Trans. Auto. Control*, to appear.

[17] A. S. Morse, "Supervisory Control," *Proc. 1993 IMA Workshop on Adaptive Control, Filtering and Signal Processing*, to appear.

[18] G. Hager, W. Chung and A. S. Morse, "Robot Feedback Control Based on Stereo Vision: Towards Calibration-Free Hand-Eye coordination," *Proc. 1994 Robotics and Automation Conference*, to appear.

[19] A. S. Morse, "Supervisory Control of Families of Linear Setpoint Controllers - Part 1: Exact Matching," *IEEE Trans. Auto. Control*, submitted.

[20] A. S. Morse, "Supervisory Control of Families of Linear Setpoint Controllers - Part 2: Robustness," *IEEE Trans. Auto. Control*, in preparation.

D. Participating Professional Personnel

- Supported:
  1. A. S. Morse, Principal Investigator
  2. F. M. Pait, Graduate Student
  3. W. C. Chang, Graduate Student
- Not supported:
  1. D. Q. Mayne, University of California, Davis
  2. G. C. Goodwin, University of Newcastle, Australia
  3. P. V. Kokotovic, University of California, Santa Barbara
  4. I. Kanellakopoulos, University of California, Los Angeles
  5. G. Hager, Yale University

E. Presentations

1. A. S. Morse, "Switching Strategies for Parameter-Adaptive Control", Center for Intelligent Machines, McGill University, February, 1992.
2. A. S. Morse, "A Gain Matrix Decomposition and Some of Its Applications, " Yale Workshop c ı Adaptive Control, May, 1992.
3. A. S. Morse " Adaptive Control of One-Parameter Families of SISO Linear Systems," 1992 IFAC Symp. on Adaptive Systems in Control and Signal Processing, Grenoble, June, 1992.
4. A. S. Morse, "High-Order Parameter Tuners for the Adaptive Control of Linear and Nonlinear Systems," U.S.-Italy Joint Seminar on Systems, Models and Feedback: Theory and Applications, Capri, June, 1992.
5. A. S. Morse, "Adaptive Control of One-Parameter Families of SISO Linear Systems," ACASP, Grenoble, June, 1992.
6. F. M. Pait, "Global Tunability of One-Dimensional SISO Systems," 1992 CDC, Tucson, December, 1992.
7. F. M. Pait, "A Cyclic Switching Strategy for Parameter-Adaptive Control," 1992 CDC, Tucson, December, 1992.
8. A. S. Morse, "Supervisory Control of Finite Families of Linear Setpoint Controllers," IMA Workshop on Adaptive control, Filtering and Signal Processing," Minneapolis, April, 1993.
9. A. S. Morse, "MIMO Design Models and Internal Regulators for Cyclicly Switched Parameter Adaptive Control Systems," 1993 ACC, San Francisco, June, 1993.
10. A. S. Morse, "Supervisory Control," Twente University, Enschede, June 1993.
11. A. S. Morse, "Lectures on Adaptive Systems," University of Groningen, Groningen, June, 1993.
12. A. S. Morse, "Dwell-Time Switching," 1993 European Control Conference, Groningen, July, 1993.
13. A. S. Morse, "Supervisory Control," University of Compiegne, France, Juny, 1993.

14. A. S. Morse, "Logic Based Switching: A Form of Intelligent Control," NASA-ARO Workshop on Intelligent Control, MIT, Cambridge, October, 1993.

15. A. S. Morse, "Supervisory Control of Linear Systems," 1993 IEEE CDC, San Antonio, December, 1993.

F. Discoveries

- **Cyclic Switching:** The discovery of this switching logic solves one of parameter-adaptive control's very long standing problems, namely how to deal with the always present points in parameter space where the design model upon which certainty equivalence control loses stabilizability. Cyclic switching is an easily implementable, practical procedure for dealing with this problem.

- **Dwell Time Switching:** We have devised a very easy to implement, provably correct method of supervisory control which significantly broadens the class of process model uncertainties to which feedback control techniques can be usefully applied. The method is intended to be used in situations where there is substantial process model uncertainty, so much so in fact that no single fixed parameter, linear control can possibly work. In particular, dwell-time switching is a logic for automatically changing a process's feedback controller, in response to a sudden, unpredictable, "large scale" change in process dynamics. The logic has been specifically tailored to perform its function without the need for applied process excitation and thus without depending on process identification. Dwell-time switching is not susceptible to error bursting, to parameter drift and other robustness problems, which at present are typical of parameter-adaptive techniques.

G. Award

A. S. Morse - Co-recipient {with I. Kanellakopoulos and P. V. Kokotovic} of the 1993 George S. Axelby Outstanding Paper Award for the paper "Systematic Design of Adaptive Controllers for Feedback Linearizable Systems,"IEEE Trans. Auto. Control, December, 1991.